• E-mail: bgtaylor@iee.org

The Transistor Revolution (Part 1)

Dr Bruce Taylor HB9ANY describes the invention of the tiny device that changed the course of radio history.

At Christmas 1938, working in their small rented garage in Palo Alto, California, two enterprising young men called Bill Hewlett and Dave Packard finished designing a novel wide-range Wien bridge VFO. They took pictures of the instrument sitting on the mantelpiece in their house, made 25 sales brochures and sent them to potential customers. Thus began the electronics company that by 1995 employed over 100,000 people worldwide and generated annual sales of $31 billion. The oscillator used five thermionic valves, the active devices that had been the mainstay of wireless communications for over 25 years.

But less than a decade after HP's first product went on sale, two engineers working on the other side of the continent at Murray Hill, New Jersey, made an invention that was destined to eclipse the valve and change wireless and electronics forever. On December 23rd 1947, **John Bardeen** and **Walter Brattain** at Bell Telephone Laboratories (the research arm of AT&T) succeeded in making the device that set in motion a technological revolution beyond their wildest dreams. It consisted of two gold contacts pressed on a pinhead of semi-conductive material on a metallic base.

The regular News of Radio item in the 1948 *New York Times* was far from being a blockbuster column. Relegated to page 46, a short article in the edition of July 1st reported that CBS would be starting two new shows for the summer season, *"Mr Tutt"* and *"Our Miss Brooks",* and that *"Waltz Time"* would be broadcast for a full hour on three successive Fridays. But right at the end, after another unexciting story about the broadcasting of road traffic reports, the article mentioned that Bell Labs had demonstrated a small metal cylinder that could *"create and send radio waves"* but contained *"no vacuum, grid, plate, or glass envelope to keep the air away".* It could amplify and oscillate and had been named a *"Transistor".*

The name had been chosen by internal ballot among Bell Labs executives and research staff. Semiconductor Triode and Surface States Triode were considered fairly good but unwieldy, and Transistor came out well ahead of Crystal Triode, Solid Triode and Iotatron. Little did the apathetic NYT reporter realise that he had witnessed the first public demonstration of an invention that would spawn a world-changing technology.

Quite independently, **Herbert Mataré** in June 1948 also invented the point-contact germanium transistor, which he called a Transitron, while working for CFS Westinghouse near Paris. By mid-1949 many of them were in use as amplifiers in the French telephone system. At this time European industry was still recovering from the devastation of war but research at UK companies such as BTH, GEC and STC was not far behind the US and their first products were named Crystal Valve and Germanium Triode as well as Crystal Triode.

The point contacts of the first transistor were created by a razorblade slit in gold foil wrapped around the edge of a triangular plastic wedge. (Bell Labs)

Origins

The roots of the invention were much older. The rectifying properties of crystals had been discovered by **Karl Braun** in 1874, before wireless existed, and the cat's whisker detectors that became popular in the early 1900s were semiconductor diodes in all but the name. Nor was the concept of a three-electrode solid-state amplifier a new one. As far back as 1926, the German-American engineer **Julius**

Research Director Ralph Bown introduces the first point-contact transistor to the press. (Bell Labs)

To the chagrin of Walter Brattain (right) and John Bardeen (glasses), Bill Shockley insisted on sitting at their workplace for this posed Bell Labs publicity photo. (Bell Labs)

Lilienfeld, who patented a forerunner to the modern electrolytic capacitor, filed a patent for an FET-like device that was granted in 1930. Since materials of the purity required weren't available at the time, it is unlikely that Lilienfeld succeeded in making a working transistor but his claim was strong enough to prevent Bell Labs from patenting the field-effect approach 18 years later.

The theoretical foundations for transistor operation were laid in 1931, when Cambridge University mathematician **Alan Wilson** formulated the quantum mechanical theory of conduction in semiconductors. He correctly attributed their properties to the presence of impurity atoms in the crystals, opening the way for less empirical work on solid-state devices. During WW2, Wilson worked on radio communications for the secret Special Operations Executive (the 'Ministry of Ungentlemanly Warfare') and later on the UK project to develop the atomic bomb. He was knighted in 1961.

With the development of the high-power 10cm cavity magnetron by **John Randall** and **Harry Boot** at Birmingham University, high resolution microwave radar became feasible if a reliable detector could be found. After Bell Labs were unsuccessful in developing thermionic valves for this very short wavelength, attention was turned once again to cat's whisker crystal diodes. In Britain, the Telecommunications Research Establishment (TRE) developed an aluminium-doped silicon cartridge that was manufactured by BTH and GEC. While at TRE, the eccentric Bristol physicist **Herbert Skinner** improvised a technique for finding a sweet spot for the contact by tapping the crystals with an old pipe-cleaner knife and these detectors famously outperformed those that were not optimised in this way. He refused to allow anyone to clean the dirty knife, which had acquired *"exactly the right momentum for the job"!*

This war effort also gave rise to the next important breakthrough. While working on radar detectors in 1940, Bell Labs chemist **Russell Ohl** made the fortuitous discovery of a rectifying junction at a defect in a bar of silicon and noted its photovoltaic behaviour. Ohl had been bitten by the radio bug when using spark transmitters on 150m during WW1 and had built a superhet as early as 1921. He coined the terms n-type, for material containing some atoms of phosphorus, antimony or arsenic (in which conduction is by electrons), and p-type, for material containing some atoms of boron, aluminium or gallium (in which conduction is by holes), and the p-n junction was born. Initially this discovery wasn't disclosed outside Bell Labs, and Ohl was instructed to cut any chance p-n junctions out of silicon that was sent to his British counterparts.

Bell Labs

Work on semiconductors at Bell Labs had begun before the war, and energetic boss **Mervin Kelly** initiated a new unified solid-state programme in June 1945, as soon as the men who had been assigned to military work began to return to the lab's new 'Idea Factory' at Murray Hill. The aim was specifically to devise an alternative to thermionic valve telephone amplifiers and the initial funding of $417,000 was billed to AT&T.

As manager of the programme, Kelly appointed **William Shockley**, a London-born physicist who had been engaged on anti-submarine warfare research during WW2. When he learned of Ohl's discovery, Shockley immediately postulated that it might be possible to make a solid-state amplifier by applying an electric field across a p-n junction but, initially, all attempts to vary the conductivity with the control field failed. Without any tools to see what was happening inside the crystals at the subatomic level, progress was dependent on intuition and trial-and-error. By January 1946 the group admitted that they were *"groping in the dark".*

However, the failures led Bardeen to postulate a theory of surface states in semiconductors and to continue experimentation. By late 1947, Bardeen and Brattain had switched from silicon to n-type germanium and felt that they were getting close to success. Then Brattain tried a configuration in which a pair of very closely spaced point contacts were created by using a razor blade to cut a minute gap in the gold foil wrapped around the edges of a small triangle of plastic. The contacts were pressed into the surface of the germanium by a spring fashioned from a paper clip. By December 16th the team had achieved significant power gain and on December 23rd they demonstrated speech amplification to Bell Labs management. An *"entirely new thing in the world"* had been created.

Patenting

Everyone at Bell Labs was familiar with the legend that their company originated because **Alexander Bell** had beaten **Elisha Gray** in a race to the patent office. So, the transistor invention was classified as Bell Labs Confidential until it was better understood and patent protection had been applied for. But in whose name? Shockley was Bardeen and Brattain's supervisor, and was disgruntled that his subordinates had made the breakthrough without his active participation. Bell Labs' lawyers advised that Shockley's own work was overshadowed by that of **Lilienfeld**, and that Bardeen and Brattain were the actual inventors. Consequently, they refused to put his name on the patent for the point-contact transistor.

Professional jealousy and bruised ego spurred Shockley into a frenzy of independent work, which he initially kept secret from the rest of the group, thus starting to alienate them. By the end of January 1948 he had come up with a theoretical transistor design that worked quite differently from that of Bardeen and Brattain, being composed of a sandwich of p-type germanium between two

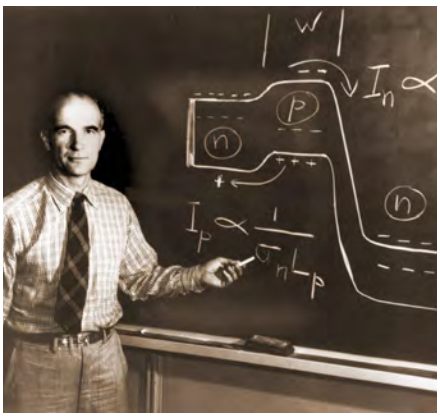
n-type regions. After it was discovered that minority carriers could indeed traverse the bulk semiconductor, the concept appeared feasible and he successfully patented this bipolar 'junction transistor' in his own name. It would eventually supersede the point-contact type but at the time no-one knew how such a device could be fabricated and it was dubbed a 'persistor' because it seemed that much persistence would be required to make it.

Meanwhile, with patent protection secured and after Naval Research Laboratory staff had withdrawn a claim that they had already made the same thing, Bell Labs announced the invention of the point-contact transistor at a press conference on June 30th 1948. Research Director **Ralph Bown** illustrated the structure of the new device with a giant cutaway model. The attendees were given headphones to hear the device amplify and oscillate and to listen to a broadcast received on a radio set that used transistors instead of valves. After the unveiling, the public showed only lukewarm interest but Bell Labs was besieged by requests for sample devices from the electronics industry and the armed forces. By the summer of 1949 the lab had fabricated 4000 working germanium transistors.

Also in that year, the US Justice Department filed a new antitrust suit against the Bell System. In view of this, as soon as the military agreed in late 1951 that transistor technology need not be classified, AT&T made manufacturing licences available without restriction to interested companies in NATO countries and Japan for the relatively modest fee of $25,000 (about $260,000 in today's money). Licensees, government labs and university researchers were given sample transistors. They were also invited to a technology symposium and a two-day transistor manufacturing plant tour at Western Electric that was attended by 100 representatives from 40 companies, including BTH, Ericsson, GEC, Philips, Siemens and Telefunken from Europe. When published in book form, a revised edition of the symposium proceedings called *Transistor Technology* was soon dubbed *Ma Bell's Cookbook*. In 1955 AT&T relinquished its original transistor patents to stave off forced divestiture, although Western Electric hung on to those covering key manufacturing processes.

In the UK, Mullard started production of the point-contact OC50 and OC51 in 1952, before launching a range of junction transistors the following year. Subsequently, over ten British manufacturers produced hundreds of transistor types for different

William Pfann (left) with an early zone refining furnace. (Bell Labs)



Shockley describes the concept of the npn junction transistor. (Bell Labs)

applications, including CV versions for military use. Mullard's *Reference Manual of Transistor Circuits* provided a useful starting guide for many amateur designers but high frequency transistors were still rare and the only transmitter described was a 5-transistor unit for the emergency frequency of 500kHz.

Crystals

While the first point-contact transistors used polycrystalline germanium, the key to the manufacture of junction transistors is the production of extremely pure single crystals that can be doped very precisely with p-type and n-type impurities. Chance often plays a vital role in discovery. In 1915, the Polish chemist **Jan Czochralski** absent-mindedly dipped his pen into a crucible of molten tin instead of his inkwell. When he lifted the pen, he found that it drew out a filament of tin that proved to be a single crystal.

Bell Labs chemical engineer **Gordon Teal** advocated developing this technique for growing large single crystals by drawing a seed slowly from a crucible of molten germanium but he received no support from Shockley or management for this work. Working evenings and weekends, he pursued the idea unofficially, shutting his apparatus away in storage during the day since there was no room for it in the metallurgy lab. By late 1949 he was able to make very pure single germanium crystals and the huge improvement compared with polycrystalline material became evident to all. For the production of wafers for modern VLSI microcircuits, the Czochralski/Teal process is still the basis of the principal method of growing silicon boules, which today may be up to 2m long and 450mm in diameter.

At the same time, **William Pfann** invented the zone-refining method of purifying a crystal ingot by using induction heating coils to displace a small molten region slowly along its length. This causes the impurities to be swept to the end of the crystal, which is eventually cut off. For silicon crystals, a variation of this technique called float zone-refining was devised in which contamination is avoided by maintaining the molten portion in place by surface tension, without a containment vessel. A similar process was also developed independently by Siemens in West Germany.

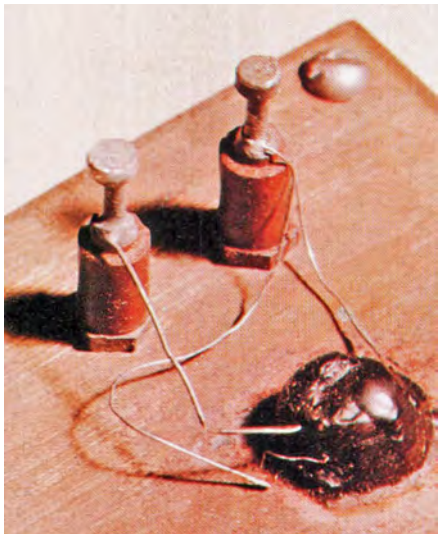
To produce the npn or pnp sandwich of Shockley's junction transistor, **Morgan Sparks** invented a double-doping method of changing the relative impurity concentrations while the crystal was being drawn from the melt, producing the first grown-junction germanium transistor in April 1950. After further refinement, Bell Labs announced this invention in July 1951. Meanwhile, the trio that had made the initial invention had broken up. Frustrated by Shockley's management style, Brattain refused to work with him again, while Bardeen left Bell Labs altogether. This was a foretaste of the problems that would later lead to the downfall of Shockley's business enterprise.

Silicon

For transistor manufacture, silicon has inherent advantages over germanium because of its greater abundance, lower leakage current and higher operating temperature range. But the material is more difficult to purify and process and, owing to the lower charge carrier mobility, a silicon transistor must have a much narrower base region for high frequency operation. It wasn't until 1961 that, with gold doping and epitaxy, a silicon transistor (the 2N709) exceeded germanium speed.

During WW2 great strides had been made in the art of purifying the material, and by 1945 silicon of 99.999% purity was available.

Gordon Teal (left) and Morgan Sparks developed the crystal growing and doping technologies that made the junction transistor possible. (Bell Labs)



The first germanium junction transistor was fabricated by Morgan Sparks in 1950. (Bell Labs)

Further improvements by DuPont allowed the first grown-junction silicon transistor to be fabricated at Bell Labs in January 1954 but in spite of this success the development wasn't followed up commercially by Western Electric, the manufacturing side of AT&T.

Meanwhile Teal had left Bell Labs to join a fledgling start-up company that would become called Texas Instruments. After telling Teal repeatedly *"This business is not for you. We don't think you can do it"*, Bell Labs finally agreed to accord a licence to TI in 1952. But instead of making only germanium transistors Teal established a group to work on grown-junction silicon transistors and 150 good ones had been made by the time of the IRE National Conference in May 1954. At the conference, speaker after speaker reported that the development of the silicon transistor would take several years so that Teal created a sensation when he revealed that he had a handful of them in his pocket and that commercial production at TI was beginning immediately. With no effective competition,

In 1954 the 4-transistor Regency TR-1 was the world's first commercial transistor radio. Over 100,000 sets were made. (Joe Haupt)

TI then dominated the market for silicon transistors for several years. The little company was suddenly in the big league.

In the UK, the TRE electronics engineer **Geoffrey Dummer**, a specialist in radar synthetic trainers, presented a fundamental paper in 1952 describing the concept of the integrated circuit. But British semiconductor manufacturers were unwilling to take the risk of investing in the idea and it would be six years before radio engineer **Jack Kilby** (**W9GTY**) of TI was awarded a patent for the first crude IC. He demonstrated that transistors, diodes, resistors and capacitors could be fabricated in a single chip, although his hybrid design required them to be interconnected by flying bonding wires. Bell Labs researchers also missed the integrated circuit and Western Electric had to enter cross-licensing agreements to make them.

Consumer Radio

In addition to hearing aids, it seemed natural that portable radio receivers would be among the first commercially made consumer products to employ transistors. Demonstration sets were shown at the 1952 Components Exhibition in Paris and at the 1953 Dusseldorf Radio Fair, where the Intermetall Corporation that had been founded by Mataré on his return to Germany demonstrated a prototype receiver that used four hand-assembled point-contact transistors.

But the established radio manufacturers were initially reluctant to change over from thermionic valves, which were cheaper than transistors at the time. So, in October 1954 Texas Instruments and Industrial Development Engineering Associates (IDEA) in Indianapolis teamed up to launch the famous $49.95 Regency TR-1. This pocket-sized MW AM set used four npn germanium junction transistors in a superhet circuit with one local oscillator/mixer, two 262kHz IF stages and one audio amplifier. (The low IF was chosen to increase the gain). Before teenagers adopted it as a personal music player, the radio was marketed as a 'security item' since the USSR was now an atomic power. In spite of its somewhat mediocre performance, the radio was a success and almost 100,000 sets were sold in the first 12 months. But having underestimated the cost of making the radio, TI hardly broke even on the venture and after that the company concentrated on making semiconductors for other manufacturers to incorporate in their products.

One of the enterprises that emulated the TR-1 was a small Japanese company called Tokyo Tsushin Kogyo (Totsuko). With little more information than a Bell Lab's licence and *Ma Bell's Cookbook*, they started manufacturing point-contact and then junction transistors, obtaining a reasonable yield of about 5%. After a false start with a portable radio whose plastic case was found to come apart in the summer heat, they launched their TR-55 model in August 1955. This 5-transistor set was Japan's first transistor radio and it spearheaded the entire Japanese consumer electronics industry. For the product launch, Totsuko's owners changed their tongue-twisting brand name to one that could more easily be pronounced in the West. They called it Sony. The name became well known outside Japan after discerning thieves who broke into a New York warehouse ignored other makes to steal only the 4000 Sony radios stored there.

In 1953 Philco developed electrolytically machined surface-barrier germanium transistors that could operate up to 60MHz and manufacturing licences were granted to other companies including Sprague and a division of Plessey. In 1955 these transistors were used in the first commercial transistor car radio and in 1958 improved versions were orbited in the 108MHz beacon transmitter carried by Explorer 1, the first US satellite.

Next month I will conclude by describing the first uses of transistors in amateur radio and more recent developments in transistor technology.

• E-mail: bgtaylor@iee.org

The Transistor Revolution (Part 2)

Dr Bruce Taylor HB9ANY concludes his look at the history of the transistor, relating how the invention impacted amateur radio and moving on to modern developments in integrated circuitry and microprocessors.

Wireless World first reported the invention of the transistor in October 1948. Using little more than a microscope, an Avometer and a pulse source for point-contact forming, enterprising amateurs were soon making their own transistors by replacing the single cat's whisker of selected germanium diodes by two. By 1950 enthusiasts in the UK were building simple receivers using commercially-available Raytheon point-contact transistors that were primarily made for hearing aids.

Radio amateurs also started experimenting with transmitters as soon as suitable transistors became available at accessible prices. The February 1953 issue of *QST* described how RCA manager K2AH even made a 146MHz CW QSO with W2UK over 25 miles with a power input of 24mW to a single selected experimental point-contact germanium T165/6 transistor. In the UK, a miniature 3.5MHz transistor transmitter by G5CV aroused great interest when operated at the 1953 Amateur Radio Exhibition. A simple receiver using two GEC point-contact transistors was described in the January 1954 issue of *Wireless World*, while a topband (160m) transmitter by G3IEE using a Mullard OC50 featured in the *RSGB Bulletin* for March. At this time manufacturers such as Philips made 'experimental transistors' available to amateurs at low prices. These were devices that failed to meet the full professional specifications and would otherwise have been scrap.

In mid-1956 IDEA launched the Regency ATC-1, a simple two-transistor mobile converter that tuned the five HF amateur bands. One germanium npn transistor acted as oscillator/mixer, with output at 1230kHz for a broadcast receiver, and a second pnp one as Q-multiplier/BFO. It was sold for $79.50.

In September of that year W1OGU, a technician with Raytheon, achieved the first transatlantic QSO with a transistor transmitter, working OZ7BO in Copenhagen and G3AAM in Birmingham on 14MHz. His crystal-controlled rig used one 2N113 germanium alloy junction transistor as 7MHz oscillator, driving a second as doubler/output stage with 78mW input.

One of the first shortwave transistor receivers for radio amateurs to be made in the UK was the Heathkit GC-1U Mohican, which was sold in 1961 for £38 15/- (around £800 in today's money). The 10-transistor kit set used three Mullard germanium AF115s as RF amplifier, local oscillator and mixer, with four OC45s for the BFO and three IF amplifiers coupled by 455kHz piezoelectric 'transfilters'. After replacing the audio output stage by a higher power amplifier, I used the compact set as a mobile receiver for several years but its performance didn't match that of good valve receivers of that period. Starting with the Model IM-30 in 1961, Heathkit also produced a series of rudimentary transistor testers and curve tracers that evolved with the device technology until the final Model IT-2232 was phased out in 1990.

It took several years for many of the traditional shortwave receiver manufacturers to change from valve to transistor designs and not all did so successfully. Eddystone's first solid-state communications receiver was the S960; virtually a model S940 with 12 transistors in place of valves. Its performance was inferior to its parent and it was dropped two years later. The more compact EC10 that was introduced in 1963 was more successful and over 6,000 were made, followed by around 10,000 of the Mk2 version with an S-meter and fine-

The 1956 Regency ATC-1 HF band converter was one of the first commercial transistor products for radio amateurs. (W8ZR)

tuning control. In 1971 you could choose between the valved Model 830 receiver and the transistorised 1830 version with slightly better performance. The 830 was Eddystone's last valve receiver and continued in production until January 1973.

National HRO receivers had been a long-time favourite with radio amateurs, and around 10,000 sets were used by the Y-Station service that supplied intercepted enemy wireless messages to Bletchley Park during WW2. In 1964 National introduced a transistor version of the receiver that retained the classic 'PW' gear drive but no longer had plug-in coils. This transitional set had 37 germanium transistors in sockets connected by conventional point-to-point wiring, just like its valve predecessors.

Diffusion

The first successful method of making a junction transistor involved creating the base layer by dropping a tiny p-type pellet into the n-type melt while drawing the crystal, and then converting it back to n-type. With this double-doping process, and also the improved rate-grown variant, it was difficult to accurately produce and connect to the very narrow base region required for high frequency performance. Problems also arose with the alternative alloy junction process developed by GE and RCA, since precise control of the alloying temperature and the thickness of the base layer was difficult. In a batch of 100 transistors, the gain could vary from 20 to 50dB.

Once again, chance played an essential role in the development of a hugely important new technology. While doping by gas diffusion had been used to introduce the donor impurities into germanium crystals, attempts to use the process at the very high temperatures required for processing silicon were initially unsuccessful because of damage to the wafer surface. But while Bell Labs chemist **Carl Frosch** was experimenting with diffusion, the hydrogen carrying the dopant impurities accidentally caught fire, causing water to be produced in his diffusion chamber. Frosch discovered that the fine green silicon dioxide layer that this formed on the surface of the wafer sealed it and protected it from damage. Unlike germanium oxides, silica is strong, inert and an excellent insulator. Initially considered a problem, the oxide turned out to be a key element of reliable solid-state electronics.

Photolithography techniques from the printing industry had already been used for the production of printed circuit boards, using a photosensitive resist that was exposed through an optical mask. The technology was readily adapted to chemically etch precisely-dimensioned windows in the oxide layer covering the silicon wafer, through which the n and p-type impurities could be diffused to make a double-diffused transistor and this important invention was announced by Bell Labs in June 1955. With the Cold War in full swing, ample military funds were available to develop these new transistors that could operate at high temperature and high frequency.

W1OGU achieved the first transatlantic QSO with a 78mW transistor transmitter in September 1952.

W1OGU's historic 14MHz transatlantic transmitter used two germanium 2N113 transistors. (Raytheon)

Nobel

It had been expected for several years that the invention of the transistor merited a Nobel Prize, so it was no real surprise when **Bardeen** and **Brattain** were chosen to receive the 1956 award for Physics. It was less certain that **Shockley** would also share the coveted prize but in the end his name was included although the vote was not unanimous. Shockley tried to find out from the Swedish Royal Academy of Sciences who had opposed him but was told that he had no right to know.

All three men attended a celebration dinner in New York but the Bardeen and Brattain families travelled to Stockholm separately from the Shockleys and only shared the formal ceremonies there. For all three Laureates, it was the pinnacle of their careers. For Shockley, it was the prelude to his demise.

Silicon Valley

In view of his abrasive management style, Shockley was repeatedly passed over for promotion at Bell Labs. So, during 1955 he left to launch his own enterprise and, with

The UK version of the 10-transistor Heathkit Mohican receiver was launched in 1961. (GM3NZI)

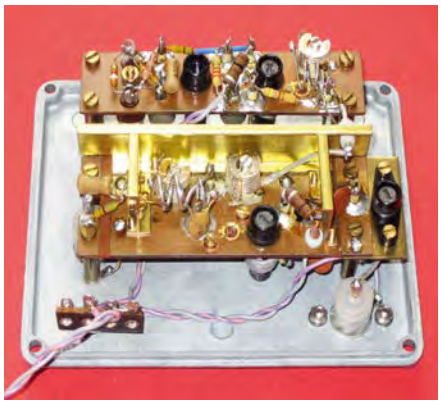
The IM-30 was the first of a series of simple transistor testers that could measure DC gain and leakage current. (Heathkit)

Early transistor receiver technology. The glass-encapsulated Mullard germanium transistors are mounted on solder sockets like little valves. (GM3NZI)

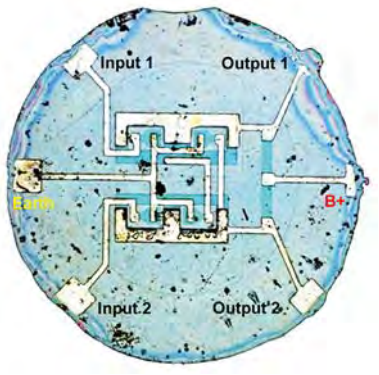
National launched the solid-state HRO 500 in 1964. It was built like a traditional valve receiver but used 37 germanium transistors and 20 diodes. (Merate Chronometer Center)

Robert Noyce (right) addresses the other seven members of the 'traitorous eight'. (Fairchild)

The 33-transistor Eddystone 1830 had a JFET/MOSFET cascode RF amplifier and dual-gate MOSFET first mixer. (Eddystone UG)



This 432MHz converter was typical of the homebrew UHF art in 1965. It uses three TI germanium pnp transistors in the UHF stages and three Mullard OC171s for the frequency multiplier and 28MHz IF amplifier. (GM3NZI)



Noyce made the first monolithic silicon IC in 1961. This basic flip-flop had four transistors and two resistors. (Fairchild)

the financial backing of Beckman Industries, Shockley Semiconductor Laboratory started up in April 1956. The facility was located in a new industrial park that was being set up in the Santa Clara Valley on land owned by Stanford University. It was the start of silicon in Silicon Valley, the extraordinary zone of innovation and technology that now accounts for one-third of all the venture capital investment in the US. Shockley planned that his company would *"set the world on fire".* Indeed, it did, but not at all as he envisaged.

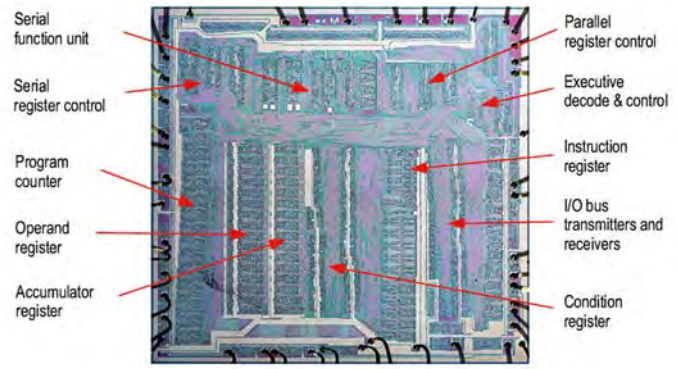
None of Shockley's Bell Labs colleagues wanted to join him. But because of his reputation as a scientific genius, he had no difficulty recruiting very talented staff, including the chemist **Gordon Moore** (of Moore's Law), Swiss physicist **Jean Hoerni** and **Robert Noyce**, who was employed at that time by the radio and TV manufacturer Philco but was seeking research-oriented work. In the UK, Ferranti began producing bipolar silicon diffused transistors in 1954. Shockley could also have directed his new team to ramp up production of silicon transistors to profit from a rapidly expanding US market. But instead, he insisted that they devote their efforts to developing a special four-layer pnpn diode that was difficult to fabricate reliably and of limited application. As a result, Shockley Semiconductor Lab never turned a profit.

Shockley proved an even worse manager in his own company than at Bell Labs. He constantly feuded with subordinates, insulted his staff and refused to listen to their advice. He became paranoid about trivial incidents, recorded all phone calls, and at one point even ordered all his employees to take a lie-detector test. Genius without ethics wasn't a winning formula and by September 1958, after a mutiny of eight dissidents lead by Noyce, the company had fallen apart. Shockley did almost no further work of scientific value and went on to pursue a racist dysgenics agenda, lecturing about the inferiority of African-Americans and advocating the sterilisation of people with an IQ under 100. He died in 1989 without fortune but knowing that he had been the intellectual driving force behind a technological revolution and the catalyst of an industry that turned a quiet Californian valley into the most concentrated source of wealth on the planet.

Planar Technology

The 'traitorous eight' that defected *en masse* from Shockley Lab went on to found Fairchild Semiconductor with a $1.38 million loan from Sherman Fairchild, a New York playboy-inventor who was the largest shareholder in IBM. Each of the eight had to make an initial investment of $500 to purchase 100 of the company's shares, a sum that Noyce had to borrow from his grandmother since neither he nor his parents had any savings. He had no difficulty repaying her with interest, for less than two years later his stock was worth $300,000 and his personal fortune was eventually to grow to over $3 billion.

The timing was fortuitous. Alarmed by the surprise launch of Sputnik 1 in October 1957, the US Military suddenly had major requirements for lightweight miniature solid-state components for its catch-up programme and total annual purchases soon exceeded $100 million. Fairchild's first contract was to manufacture silicon mesa transistors for IBM's navigational computer for the XB-70 Valkyrie bomber. To make arrays of transistors, they cobbled together a step-and-repeat camera using ordinary 16mm movie camera lenses. The yield was reasonable but reliability proved an issue and technicians had to 'tap test' the transistors with pencil erasers to check



The 1976 Ferranti F100L was the first 16-bit microprocessor designed and manufactured in Europe. It used an enhanced rad-hard bipolar technology with 3.5 micron features. (Ferranti)

Inexpensive SDR dongles spawned a new generation of communications receivers. (HB9ANY)

whether tiny loose particles trapped in the hermetic package could contaminate the exposed p-n junctions.

To solve this problem, Hoerni built on the earlier work of Frosch to invent the ground-breaking planar technology that protected the sensitive junctions with oxide and allowed all the contacts to be made on one side of the silicon wafer. This passivation process reduced leakage currents and the configuration automatically created graded bases that reduce the charge carrier transit time, as in drift transistors. It also supported the aluminium-over-oxide interconnection scheme that was used by Noyce to make the first commercial monolithic silicon integrated circuits in 1960, after the problem of aligning successive photolithographic masks had been solved. Patent litigation between Fairchild and TI over the invention of the IC lasted many years but out of court the two companies entered a cross-licensing agreement with a net payment to Fairchild.

The individual components in the production versions of these ICs were isolated by reverse-biased p-n junctions, a technique that had been patented by **Kurt Lehovec** while at Sprague Electric, who paid him only $1 for the rights to this key invention. (A common practice at the time). Until it was overtaken by TI in 1967, Fairchild became the undisputed leader of the semiconductor industry and in due course, spin-off 'Fairchildren' spawned the creation of dozens of successful companies in Silicon Valley, such as AMD, Intersil, National Semiconductor, Signetics and Teledyne.

The silicon dioxide layer also proved the key to neutralising the troublesome surface states that had thwarted attempts to make an insulated-gate field-effect transistor. **John Atalla** finally succeeded in making a working FET at Bell Labs in 1959, paving the way for modern MOSFET integrated electronics. In the UK, Plessey was involved in integrated circuit development at an early date but the first ICs to be produced commercially in Europe were the Micronor devices introduced by Ferranti from 1962. These ICs had a wired OR function and were used mainly in computers developed by Marconi for the Admiralty. The second generation of this family used an enhanced DTL technology that was faster but less dense than TI 74 series TTL, which emerged as the most popular logic configuration after it appeared in 1966. Micronor II ICs powered the Argus 400 computers that were used in many industrial control applications, such as nuclear power stations and the Jodrell Bank radio telescope. In 1966, Plessey started the first European production of MOS ICs at Swindon.

Evolution

In 1968 Moore and Noyce left Fairchild to found Integrated Electronics Corp, a name they abridged to the snappier Intel. Inspired by HP, they practised a non-hierarchical management style that encouraged the exchange of ideas and innovation and in 1971 their four-bit 10-micron 4004 CPU chip with 2300 MOS transistors launched the microcomputer age. At that time few people envisaged the wide-ranging consequence of the synergy of microprocessors and wireless, and in the same year a marketing study commissioned by AT&T reported that *"there is no market for mobile phones at any price"*!

The first European 16-bit microprocessor was the Ferranti 3.5-micron F100L, introduced in 1976. This mil-spec rad-hard chip, designed in Bracknell and fabricated in Manchester, had about 7000 components and 2m of aluminium track interconnects. It was orbited in OSCAR-9, although it wasn't frequently enabled in that satellite because of its high power consumption. Two years later Intel introduced the commercial 16-bit 3-micron 8086 microprocessor and the x86 family architecture rapidly became ubiquitous in desktop PCs and laptops. In due course this led to the next iteration in wireless technology. Although the concept was much older, in 1995 **Stephen Blust** coined the term Software Defined Radio and soon SDR hardware and software allowed any PC to be turned into a high-performance transceiver capable of handling a wide range of communications modes.

Today there are 19 silicon manufacturing facilities in the UK. A single modern FPGA can have as many as 50 billion microscopic transistors and (including memory) a high-end smartphone contains a total of around one trillion, or ten times more than the number of neurons in the human brain. To visualise the total number of transistors that have been manufactured, we can take as a metric the number of cells in the human body – about 100 trillion. Then a Fermi estimate of the total number of transistors made since 1947 exceeds the number of human cells in the entire population of the UK and within a few years the number of transistors produced may equal the number of human cells on the planet. Even visionaries like **Bill Hewlett** and **Dave Packard** would have been astounded.

In the years immediately following its invention, the transistor was conceived as a replacement for the thermionic valve. Indeed, it was, and a very good one but it also triggered revolutionary growth in communications technology and created a world that has become interconnected as never before. Apart from wireless itself, perhaps no other modern invention has had a greater influence on almost every aspect of our daily lives.